The Younger Dryas and Millennial-Scale Oceanographic Variability in the Sulu Sea, Tropical Western Pacific

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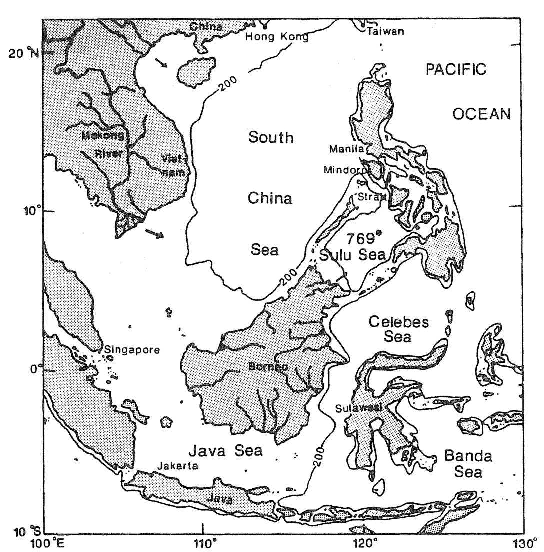
ABSTRACT: A high resolution, AMS ^{14}C-dated sediment record from the Sulu Sea clearly indicates the Younger Dryas climatic event affected the western equatorial Pacific (Linsley and Thunell 1990). Presence of the Younger Dryas in the tropical western Pacific indicates this climatic event is not restricted to the North Atlantic nor to high latitudes, but is global in extent. In addition, the planktonic $\delta^{18}O$ record and bulk $CaCO_3$ records both reveal millennial-scale variability. Spectral analysis of the $\delta^{18}O$ record shows increased variance at 2.5 Ka. The $CaCO_3$ accumulation rate record also shows increased variance at 2.5 Ka and at 3.5 Ka, with the 2.5 Ka cycle dominant after about 13 Ka. Similar ~2.5 Ka millennial climatic cycles have been recorded in late Pleistocene $\delta^{18}O$ records from the Indian Ocean, Quaternary continental and alpine glaciers, Holocene tree rings, and in Permian varved evaporite deposits, suggesting that about 2.5 Ka is an inherent climatic rhythm. The Younger Dryas occurs within these millennial cycles, suggesting its occurrence in the Indonesian tropics may be an expression of a 2.5-Ka millennial-scale climate cycle. In this context, the Younger Dryas is not unique, but apparent in numerous paleoclimatic records due to the rapid climatic change during the last deglaciation.

Introduction

High-accumulation-rate deep-marine sediments as found near continental margins offer the opportunity to examine higher frequency oceanographic and climatic change than open-ocean records with lower accumulation rates. The Sulu Sea, in the humid Indonesian tropics of the western Pacific, is a deep basin (>4800 meters) surrounded by a shelf most of which is less than 100 meters deep (Figure 1).

Figure 1
WESTERN TROPICAL PACIFIC
SHOWING LOCATION OF SULU SEA

Bathymetric contour is the 200-meter isobath.
Note location of Site 769A.



Tropical monsoonal climatic conditions and tectonic activity in the region have created one of the highest fluxes of river-borne sediment in the world (Milliman and Meade 1983). As a result, sedimentation rates are generally high. The isolated configuration of the Sulu Sea restricts circulation in the basin, resulting in anomalously warm and dysaerobic deep waters. The low dissolved oxygen content of intermediate and deep waters combined with high sediment accumulation rates has resulted in reduced benthic mixing of sediments.

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Oceanographic conditions in the Sulu Sea are strongly influenced by the monsoonal climate of the Indonesian region and by the quasi-permanent Indonesian low pressure system. In addition, the Indonesian region was climatically important during the Pleistocene because vast areas of shallow shelves were exposed during sea level low stands. Sea level changes would have strongly influenced oceanographic conditions in the Sulu Sea, where a drop of 120 meters during the last glacial maximum (Curray 1964, Milliman and Emery 1968, Fairbanks 1989) is sufficient to almost isolate the basin from surrounding seas, potentially changing surface and deep water conditions.

To elucidate high-frequency oceanographic and climate change in the Sulu Sea, the upper 3.5 meters of sediment from Ocean Drilling Program (ODP) Hole 769A was sampled at 2.5-centimeter intervals. Sedimentation rates in this portion of the record range from 11 to 16 cm/Ka. The detailed sampling (about 250-year intervals) spans the last 22 Ka. The high sedimentation rates and close sampling interval yield a record comparable in resolution to that of core V23-81, the "type-section" for the Younger Dryas in the North Atlantic (Broecker *et al.* 1988).

Detailed time series of planktonic foraminiferal $\delta^{18}O$ and species abundances record the presence of the Younger Dryas between about 11 and 10 Ka (Linsley and Thunell 1990). In addition, the *Globigerinoides ruber* $\delta^{18}O$ data and $CaCO_3$ accumulation data record 2.5-Ka millennial-scale oceanographic variability, with the Younger Dryas falling within these millennial cycles. This paper presents evidence for millennial-scale variability and a brief discussion of the relationship of the Younger Dryas in the Indonesian tropics to a millennial climate cycle.

The Younger Dryas Climatic Event

It has been suggested that during the transition from the last glacial climatic regime to the Holocene, a brief return to glacial-like conditions, referred to as the Younger Dryas, occurred between about 11 and 10 Ka. The Younger Dryas has primarily been identified in records from Europe (Bjorck and Moller 1987, Lundquist 1987, and Manqerud 1987) and from the North Atlantic (Ruddiman *et al.* 1977, Ruddiman and McIntyre 1981a and 1981b), although a number of recent studies have documented a Younger Dryas-like event in areas far removed from the North Atlantic (Chinzei and Oba 1986, Chinzei *et al.* 1987, and Kallel *et al.* 1988).

Recently, using radiocarbon-dated submerged coral reefs from Barbados, Fairbanks (1989) showed that the transition from the last glacial maximum to the Holocene was marked by two periods of extremely rapid sea level rise, centered at about 12 and 9.5 Ka. The Younger Dryas occurred between these two periods.

In the Sulu Sea, planktonic foraminiferal $\delta^{18}O$ and abundance data both record significant changes during Younger Dryas time (Linsley and Thunell 1990). In particular, a 0.4 parts per mil increase in the $\delta^{18}O$ value of *Globigerinoides ruber* (white variety) and the reappearance of the cool water planktonic foraminifera, *Neogloboquadrina pachyderma* dextral, occur during the Younger Dryas at this location. Their data do not show whether the Younger Dryas event in the Sulu Sea is the result of surface water temperature changes, salinity changes, or a combination of both. Changes in surface salinities could have been accomplished through local or global processes. They conclude that a salinity change is the more plausible explanation.

Specifically, a comparison of the Sulu Sea $\delta^{18}O$ record with the estimated $\delta^{18}O$ change of mean ocean water (Fairbanks 1989) suggests the period immediately preceding the Younger Dryas was a time of lowered surface water salinities. Intensification of the monsoon climate system and increased precipitation at about 11 Ka is one mechanism that may have resulted in local salinity changes. Meltwater pulses from the Tibetan Plateau is another possible cause.

Oceanographic Setting

Surface waters of Southeast Asian Seas have high temperatures and low salinities typical of humid tropical regions. The large excess of rainfall over evaporation creates an average surface salinity of 34 parts per mil. Annual temperature variations in the region are less than 2°C, but salinity is extremely variable because of high rainfall and river runoff and the intricate geographical structure of the area (Wyrtki 1961).

The Mindoro Strait, at 420 meters deep, controls the deep-water ventilation rate in the basin (see Figure 1) (Frische and Quadfasel 1990, Wyrtki 1961, and Van Reil 1943). Currently, deep water below the thermocline is uniformly warm (10°C), is dysaerobic, and has the same physical properties as water entering from the China Sea. Concentration of dissolved oxygen is low throughout the deep waters (<1.2 ml/L), corresponding to only 20% saturation at the prevailing salinity and temperature.

Warm bottom waters in the Sulu Sea result in excellent biogenic carbonate preservation. The carbonate compensation depth (CCD) is currently at ~4800 meters, while the carbonate lysocline occurs near 4000 meters (Linsley *et al.* 1985, Exon *et al.* 1981, Thunell Unpublished Data). In contrast, in the South China Sea the CCD is at 4000 meters and the lysocline is at 3500 meters (Rottman 1979). The South China Sea is open to the western Pacific and is well aerated at depth by cold bottom water.

Methods

Ocean Drilling Program (ODP) Leg 124 cored Site 769 at 3643-meter water depth on a bathymetric high in the center of the Sulu Sea (see Figure 1). This site was chosen specifically to avoid turbidite sedimentation and to obtain a continuous, high-resolution Neogene record. Samples were taken at 2.5-cm intervals in the upper 3.5 meters of core collected at Hole 769A for a high resolution study of the last deglaciation. Analytical methods for the isotopic analysis of *G. ruber* (white variety, 250-400 μm size fraction) and the planktonic foraminiferal faunal analyses are discussed in Linsley and Thunell (1990). Replicate sample analysis yielded a standard deviation from the mean of ±0.07 parts per mil for $S^{18}O$.

Calcium carbonate analyses were performed at 5-cm intervals. Samples were freeze-dried, and a split of each sample was analyzed for bulk $CaCO_3$. Carbonate carbon was measured by titration using a Coulometer, with replicate analyses yielding a standard deviation of ±0.5%. $CaCO_3$ mass accumulation rates (MAR; $g/cm^2/Ka$) were calculated following the methods of Gardner *et al.* (1984) using the continuously measured wet-bulk density (WBD) obtained from the shipboard gamma-ray attenuation porosity evaluator (GRAPE). WBD was converted to dry-bulk density (DBD) by the following relationship: DBD g/cm^3 = WBD g/cm^3 – (0.01025 × porosity) (van Andel *et al.* 1975). The product of the average accumulation rates and the DBD gives bulk sediment MAR ($g/cm^2/Ka$). Mass accumulation rates of bulk $CaCO_3$ were determined by multiplying the bulk accumulation rate by the weight percent $CaCO_3$ fraction in the sample.

Age Model

The chronology for the upper 350 centimeters of Hole 769A is based on three AMS ^{14}C ages. Specimens of *G. ruber* yielded corrected ages of 9,720 ±80 years from 107 cm, 11,100 ±185 years from 128 cm, and 18,320 ±155 years from 245 cm. A correction factor of –400 years was applied to each date to account for the difference in ^{14}C between the atmosphere and surface water (Bard 1988).

Ages for individual samples were estimated assuming constant sedimentation rates between ^{14}C dates. Sample ages for the upper part of the core (above the first ^{14}C date) were derived assuming the top of the core has an age of zero. Likewise, sample ages below 245 cm (18,320 years) were extrapolated using the sedimentation rate calculated for the core interval from 128 to 245 cm. The ^{14}C ages indicate sedimentation rates in the core vary from ~11 cm/1000 years during the Holocene to ~16 cm/1000 years during the last glacial.

Analytical Results

The $\delta^{18}O$ and CaCO3 MAR records are displayed in Figure 2. The high resolution $\delta^{18}O$ time series reveals small (~0.3 parts per mil) millennial oscillations during the last 25 Ka, which may be related to salinity changes (Linsley and Thunell 1990). $CaCO_3$ MAR shows high-frequency fluctuations from glacial stage 2 through the Holocene. At 11 Ka (the beginning of the Younger Dryas), $CaCO_3$ accumulation reaches high values of ~2.5 $g/cm^2/Ka$ and then decreases to relatively low values of ~1.7 $g/cm^2/Ka$ between ~11 and 10 Ka.

Spectral characteristics of the last 25 Ka of the *G. ruber* $\delta^{18}O$ record and bulk $CaCO_3$ MAR record were examined using standard time series procedures (Jenkins and Watts 1968) (Figures 3 and 4). For the $\delta^{18}O$ record, the upper 3.5 meters of Site 769A was interpolated at 250-year intervals. The $CaCO_3$ record was interpolated at 400-year intervals due to its 5-cm sample interval. One-third lags of the autovariance function were used to estimate the spectra. A prewhitening filter was used to emphasize the higher frequency variability.

Spectral analysis indicates that for $\delta^{18}O$, significant variance is concentrated at a period of 2.5 Ka, with a broader, less defined increase in variance at about a 1.5 Ka period. The 2.5-Ka millennial oscillations are absent from 9.0 Ka to the present. Spectral analysis of the $CaCO_3$ record indicates variance is also concentrated at 2.5 Ka, as well as at 3.5 and 1.7 Ka, with the 2.5 Ka cycle dominant between about 13 Ka and 5 Ka.

Figure 2
OXYGEN ISOTOPIC PROFILE OF *G. RUBER (above)* (250-Year Sample Interval) AND CALCIUM CARBONATE MASS ACCUMULATION RATE RECORD *(below)* (400-Year Sample Intervals)

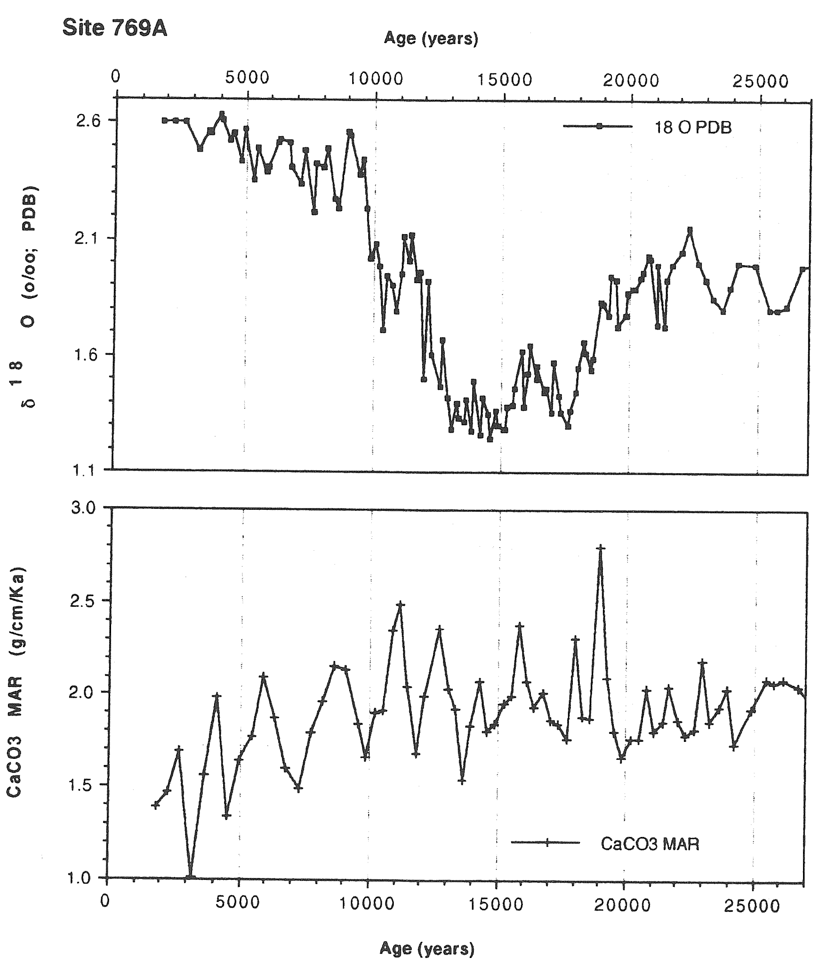


Figure 3
SPECTRAL ESTIMATES OF $\delta^{18}O$ OF THE PLANKTONIC FORAMINIFERA *G. RUBER* FROM SITE 769A (0-4 meters)

The upper 4 meters was interpolated at 250-year intervals. One-third lags of the autovariance function were used to estimate the spectra. A prewhitening filter has been used to emphasize the higher frequency variability. Variance is concentrated at 2.5 Ka, with a broader peak at about 1.5 Ka. The bandwidth and 95% confidence interval are shown.

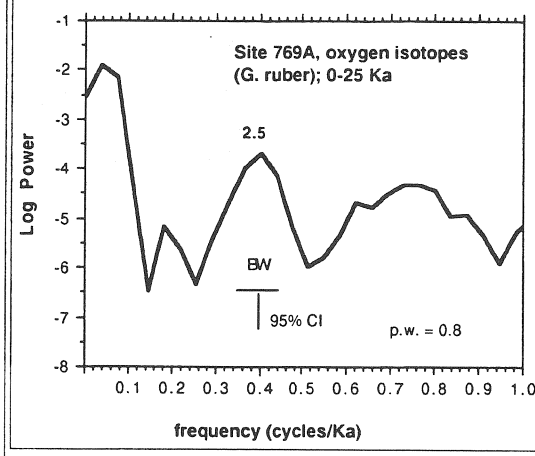
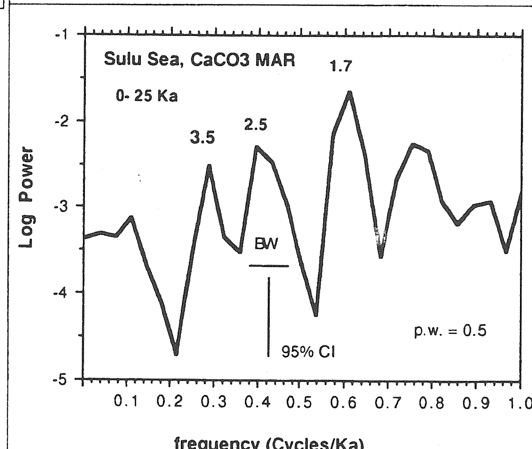


Figure 4
SPECTRAL ESTIMATES OF BULK CALCIUM CARBONATE FROM SITE 769A (0-4 meters)

Due to a 5-cm sample interval, the upper 4 meters of calcium carbonate record was interpolated at 400-year intervals. One-third lags of the autovariance function were used to estimate the spectra. A prewhitening filter has been used to emphasize the higher frequency variability. Variance is concentrated at 1.7, 2.5, and 3.5 Ka, very similar to the spectral estimates of the $\delta^{18}O$ record from this site. The bandwidth and 95% confidence interval are shown.



Stable Isotopic and Faunal Signature

The Barbados sea level record (Fairbanks 1989) shows two meltwater events, just before (~12 Ka) and just after (~9.5 Ka) the Younger Dryas. In this context, the Younger Dryas is not unique but is distinguished because it was a brief interval between two periods of lowered surface salinities. According to Fairbanks (1989), the extremely high discharge rates during these two meltwater pulses caused rapid decreases in the $\delta^{18}O$ of surface waters.

Examination of the Hole 769A $\delta^{18}O$ record reveals that Younger Dryas time is indeed bracketed by two brief intervals of light $\delta^{18}O$ values that may be equivalent to the two meltwater pulses identified by Fairbanks (1989). Specifically, there is a 0.85 parts per mil decrease in $\delta^{18}O$ between 15 and 11.5 Ka in the Sulu Sea record (Figure 2). In comparison, the $\delta^{18}O$ change of mean ocean water was only 0.4 to 0.5 parts per mil during this period (Fairbanks 1989). If this difference was due to a local salinity change, and if the deglacial $\delta^{18}O$/salinity relationship was similar to that for the modern North Pacific (Craig and Gordon 1965), then surface water salinities in the Sulu Sea at 11.5 Ka would have been about 1 parts per mil lower than during Younger Dryas time.

Similarly, the difference in $\delta^{18}O$ between 15 Ka and 10.5 Ka (mid-Younger Dryas time) in our Sulu Sea record is only 0.5 parts per mil (Figure 2), about equal to the $\delta^{18}O$ change of mean ocean water at this interval. This suggests $\delta^{18}O$ values in the Sulu Sea during Younger Dryas time were not anomalously *heavy*, but rather that the preceding 1,000 years was a time of anomalously *light* $\delta^{18}O$ values. This may also be the case for the other millennial-scale oscillations in the $\delta^{18}O$ record.

Numerous rivers drain into the region, potentially affecting the $\delta^{18}O$ record. In particular, the Mekong River, which has headwaters in the Tibetan Plateau, empties into the southern end of the South China Sea (Figure 1). The Mekong River has a discharge of 470 km^3/year, the ninth largest river in the world (Boreland 1973). For comparison, the Mississippi River, the sixth largest in the world, has a discharge of 580 km^3/year (Milliman and Meade 1983).

Calcium Carbonate Accumulation

The high-frequency $CaCO_3$ oscillations at Site 769A do not appear to be related to dissolution/preservation cycles. The planktonic foraminifera are remarkably well preserved throughout the 25-Ka record except for a brief interval between 0.25 and 0.40 meter, which also contains abundant volcanic ash. In addition, the pteropod and $CaCO_3$ MAR records do not seem related, supporting the lack of a dissolution effect on the $CaCO_3$ record.

During the Younger Dryas, $CaCO_3$ MAR exhibits a sharp decrease, slightly lagging the $\delta^{18}O$ record. However, similar decreases occurred repeatedly throughout the last 25 Ka, so this is not a unique expression of the Younger Dryas. Grain-size analysis of the terrigenous fraction in these samples shows no correspondence to the $CaCO_3$ oscillations, suggesting terrigenous dilution is not the cause. Trace metal data from the longer record from Site 769A, spanning the last 750 Ka, suggest glacial times had higher rates of productivity and greater accumulation rates of certain trace metals and $CaCO_3$ (Linsley and von Breymann in press). This is in accord with results of Romine (1982) and Rea *et al.* (1986), who find greater equatorial wind shear during glacial times, which could have affected hydrographic dynamics of the western Pacific and Sulu Sea. A thicker warmwater lens in the western Pacific and reduced amounts of high total CO_2 Pacific Intermediate water could have affected the CO_2 content of Sulu Sea deep water. Although the cause of these $CaCO_3$ cycles at Hole 769A remains unclear, primary productivity changes and variable carbonate flux to the sea floor appear to be the most plausible explanation.

Possible Relationship of the Younger Dryas to Millennial Climatic Variability

Data from Hole 769A suggest that an additional hypothesis regarding the origin of the Younger Dryas should be considered. The proxy evidence of oceanographic and climatic change found at Hole 769A suggests millennial-scale oceanographic variability has influenced the Sulu Sea. At Hole 769A, the Younger Dryas occurs within this millennial cycle, which is most clearly expressed in the $CaCO_3$ accumulation and $\delta^{18}O$ records.

Evidence for millennial-scale climatic variability has been found in a variety of high accumulation rate geologic settings. A 2,500-year climatic cycle is depicted in a summary spectrum of climatic variability compiled by Mitchell (1976).

Evidence for a millennial cycle has also been documented in the advance and retreat of Quaternary glaciers (Denton and Karlen 1973) and in the H/D isotopic ratio and CO_2 concentration of late Pleistocene glacial ice (Oeschger *et al.* 1985). Oxygen isotopic records (Dansgaard *et al.* 1984, Benoist *et al.* 1982) and deuterium isotopic records (Yiou *et al.* 1989) from Quaternary ice cores from Antarctica and Greenland display about a 2.5 Ka period, as well as others between 2 and 15 Ka. These records reflect changes in surface air temperature.

In late Pleistocene-Holocene marine records, Pestiaux *et al.* (1987) have documented spectral density peaks at 10.2, 4.6, and 2.3 Ka in planktonic $\delta^{18}O$ records from the monsoonal region of the Indian Ocean. They suggest the climatic system is characterized by a highly nonlinear response to orbital forcing. Millennial-scale changes in upwelling and productivity in the eastern Pacific appear in time series records compiled by Pisias (1978) and Juillet-leclerc and Schrader (1987). Off the coast of Northern California, millennial-scale upwelling variability in the late Pleistocene has been recorded by alternately varved and bioturbated sediments (Linsley *et al.* 1990, Anderson *et al.* 1990). In addition, the Barbados coral sea level record of the last 17,000 years compiled by Fairbanks (1989) documents two distinct meltwater pulses centered at 12.0 and 9.5 Ka. The timing of these increases in meltwater discharge appear to fit within a millennial cycle, although there is no astronomical explanation for separate meltwater pulses.

In the Permian, the varved evaporitic Castle formation records strong salinity cycles manifested as Halite bedding thickness changes (Anderson 1982). The average period of the oscillations is about 2,500 varve years, with increased variance between 1800 and 3000 years.

Causes of these millennial-scale paleoclimatic fluctuations are not known. Pestiaux *et al.* (1987) have suggested that an approximate 2.5 Ka period is one of several harmonics of the 19- to 23-Ka precession and 41-Ka obliquity orbital cycles. The presence of these harmonics was predicted by LeTreut and Ghil (1983) and LeTreut *et al.* (1988) using nonlinear climatic oscillator models. Millennial-scale periodicity has also been attributed to changes in solar activity (Bray 1971, Denton and Karlen 1973, Anderson 1982, and Anderson *et al.* 1989 and 1990). The solar activity hypothesis is supported by the ^{14}C record in Holocene tree rings, a proxy for solar activity. The tree-ring records contain a dominant periodicity at 2.4 Ka (Suess 1980, Damon and Linwick 1986, Stuiver and Braziunus 1989).

Whatever the cause of the ~2.5 Ka millennial climatic cycle, in the Sulu Sea the position of the Younger Dryas within millennial cycles in $\delta^{18}O$ and $CaCO_3$ suggests the occurrence of the Younger Dryas in the Indonesian tropics may be an expression of a millennial-scale climatic cycle. In this context, the Younger Dryas is not in itself a unique event. Lack of significant millennial $\delta^{18}O$ oscillations after about 9 Ka and the change in the period of the $CaCO_3$ cycles at about 13 Ka suggest changes in climatic boundary conditions during deglaciation are somehow responsible.

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